FRG: Quantum Engineering of Metallic and Magnetic Nanostructures

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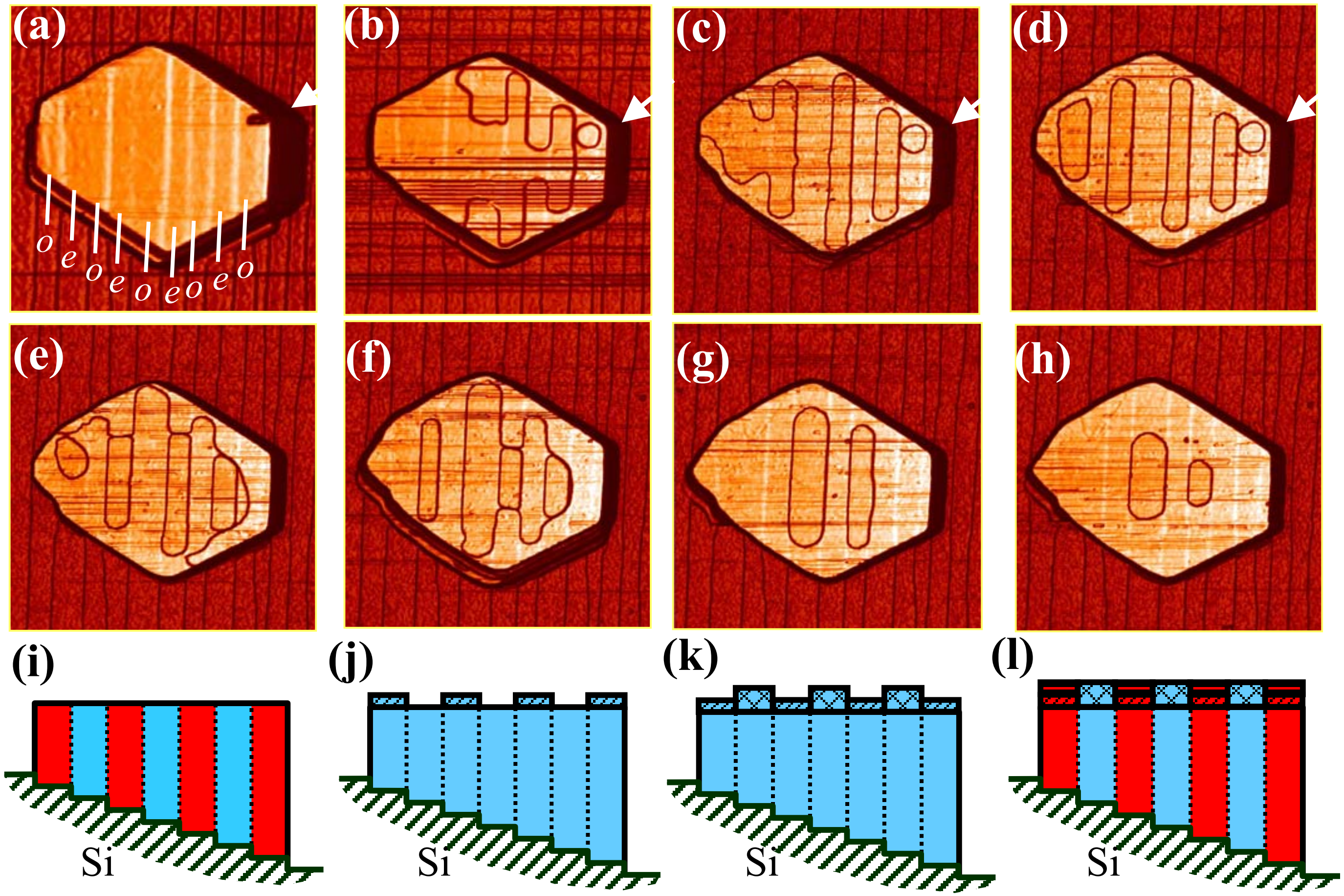
Swinging nanostructure as a free energy pendulum



(The red column corresponds to the odd-layered regions)

In collaboration with Q.K. Xue (CAS) and D. Chen (Roland Institute)

- Free energy cost from surface steps is the usual driving force for smoothening metallic overlayers on a substrate. For very thin film, it was discovered that quantum size effects (QSE) can dominate the film stability [PRL **80,** 5381 (1998)]. For Pb grown on flat substrate of Si(111), it was known that QSE manifests an oscillatory stability of the film thickness: For a particular range of thickness, QSE favors an even number over an odd number of film thickness [PRL **80,** 5381 (1998); PRL **86**, 5116 (2001)]. On a stepped substrate, however, a flat-top thin film geometry inevitably contains a mixture of both odd and even number layers such as the one shown in Fig. 1(a). In this case, the QSE is "frustrated." (see also schematic in Fig. 1(i))
- Interestingly, by exploiting such an intrinsic instability of the Pb wedge using a scanning tunneling microscope (STM), we can jump start mass transport of millions of atoms (triggering position indicated by the arrow in Fig. 1(a)) that exhibit a very intriguing dynamical behavior: The system first chooses to maximize the QSE by growing primarily in local regions with an odd number of layer thickness to remove the "frustration" of QSE (Fig. b-d and j), however, at an expense of having high step energy; it then turns around to minimize the step energy by making a flat-top surface like Fig. 1(a), however, at an expense of having a state with frustrated QSE. In this sense, like a classical pendulum, the mass transport of millions of atoms swing between two extremes – maximization of QSE and the minimization of the step energy (but with the creation of frustrated QSE).
- Remarkably, the system can jump from one maximized QSE state (Fig. 1(j)) to another maximized QSE state (Fig. 1(k)) via a double-layer growth mode. Following a new trigger pulse at the completion of the strip-flow growth on the odd-layered regions (Fig. 1(d)), growth on the even-layered regions are initiated and characterized by a simultaneous two-layer growth (Figs. 1(e) and 1(f)). The double-layer growth ceases when the initial even-layered regions in Fig. a are covered by two layers of Pb, and as a result the system remains in a state with "frustrated" QSE.
- -- This work was in collaboration with Prof. Q.K. Xue of the Institute of Physics, Chinese Academy of Science and D. Dongmin Chen of the Roland Institute at Harvard University. The work was submitted to Nature

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Epitaxial growth and magnetic properties of Mn_3Ge_5 on Ge(111)

Spin-electronics or "spintronics" utilizes the quantum mechanical spin of the electron to carry or store information. We discovered a novel *epitaxial* metal/semiconductor interface with high ferromagnetic Curie temperature and good potential for spin injection in a silicon-compatible geometry, namely ferromagnetic Mn_5Ge_3 thin films on Ge(111). The crystalline quality, surface topography, and thermal stability of the films indicate the possibility of growing epitaxial Ge on top of Mn_5Ge_3 so that epitaxial trilayers or "spin valves" and perhaps even multilayer structures can be fabricated.

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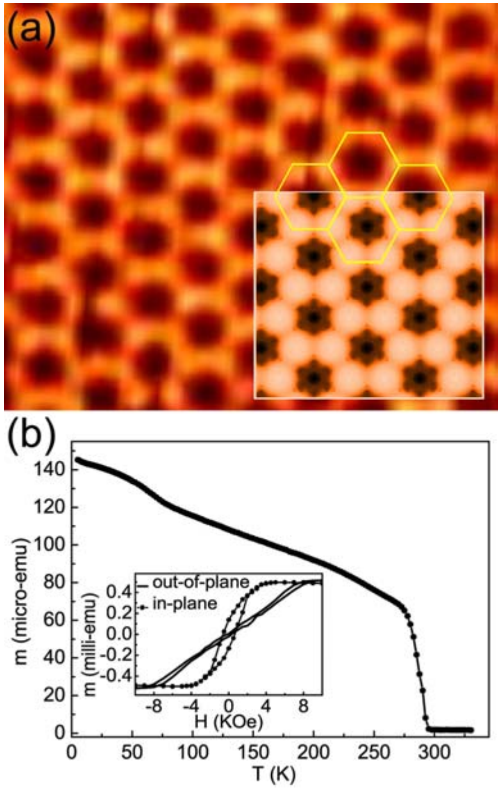

Atomic structure (a) and magnetic data (b) of $Mn_5Ge_3(0001)$ on Ge(111)

- The objective of this part of the program is to create semiconductors with ferromagnetic ordering temperatures ("Curie temperatures") that exceed room temperature by a comfortable margin and to create atomically abrupt interfaces between magnetic and non-magnetic semiconductors to enhance the efficiency of spin diffusion across interfaces. These novel materials are grown using molecular beam epitaxy, an advanced growth technique that allows researchers to create artificially structured materials that cannot be grown under thermodynamic equilibrium conditions. The synthesis efforts are guided by theory efforts, aimed at predicting the proper growth conditions and magnetic properties.
- The project has resulted in the discovery of a novel epitaxial metal/semiconductor interface with good potential for spin injection in a silicon-compatible geometry, namely ferromagnetic Mn5Ge3 thin films on nonmagnetic Ge(111). The Mn5Ge3 films have a ferromagnetic ordering temperature of 296 K, *i.e.* room temperature. The crystalline quality, surface topography, and thermal stability of the films indicate the possibility of growing epitaxial Ge on top of Mn5Ge3 so that epitaxial trilayers or "spin valves" and perhaps even multilayer structures can be fabricated for spintronics research and applications. In contrast to germanides, silicides either have low T_c or are not ferromagnetic at all. Drawing the logical parallel to the promise of epi-silicides for Si-based microelectronics, ferromagnetic epi-germanides may hold great potential for germanium-based spintronics. <u>Furthermore, the established compatibility of Ge and Si may allow integration into mainstream silicon electronics.</u> This work has been accepted for publication in Applied Physics Letters.

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Education:

New personnel recruited for in this project are 1 undergraduate student (J. Robertson), 2 graduate students (S. Qin, D. Culcer), and 1 postdoc (J. Li). These students and postdoc joined the project after Aug. 2003. There are two continuing postdocs (N. Liu and B. Wu) who are partially supported by the this program.

Outreach:

We have recruited a student (Bernard Niu) from Westlake high school who worked in Shih's lab on computer interfacing with instrumentation in the summer of 2003.

Shih also created a new inter-disciplinary course "Nanostructure Characterization Techniques". The course is now part of the core courses for the new Ph.D. portfolio program in Nanoscience and Nanotechnology at the University of Texas at Austin